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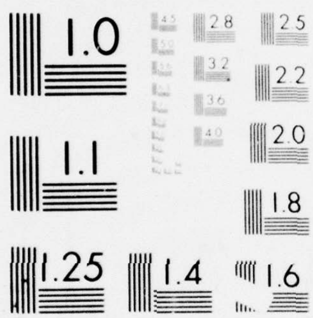
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METHOD FOR CALCULATING ICE LOADS ON HIGH STRUCTURES

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CORPS OF ENGINEERS, U.S. ARMY
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The indirect calculation of ice loads on high structures, using cloud and precipitation characteristics at subzero temperatures, is discussed. Results of experimental calculations of ice load probabilities made for heights 100, 200, 300, 500, and 600 m above the ground, using station observations are presented. The values of ice loads, and thicknesses of ice covers, determined arithmetically, are compared with observed values obtained from a mast in Obninsk. It is shown that the proposed method is sufficiently accurate.

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NOTICE

A METHOD FOR CALCULATING ICE LOADS ON HIGH STRUCTURES

M. V. Zavarina, V. G. Gluchov, M. N. Mytarev

Summary. The indirect calculation of ice loads on high structures, using cloud and precipitation characteristics at subzero temperatures, is discussed. Results of experimental calculations of ice load probabilities made for heights 100, 200, 300, 500, and 600 m above the ground, using station observations are presented. The values of ice loads, and thicknesses of ice covers, determined arithmetically, are compared with observed values obtained from a mast in Obninsk. It is shown that the proposed method is sufficiently accurate.

The characteristics of the regime of glaze ice and rime phenomena in the air layer near the ground have been studied in the Soviet Union for some years now. The results were used to compile "References for Calculating Ice, and Combined Ice and Wind Loads."

Considerably less attention has been given to the study of the regime of glaze ice and rime phenomena in the boundary layer, although such data are frequently required in connection with the intensive construction of high structures.

Regular measurements of ice deposits at great heights have been made in the USSR up to now only at two stations, in Ostankino and Obninsk, which, moreover, are not very far from each other [6, 7]. These measurements are highly important in the study of the processes involved in the growth of ice on sections of high structures, but are inadequate for setting limits on the intensity with which ice will deposit on sections of high structures located on different parts of Soviet territory with great physical and geographic differences.

It is difficult to calculate icing probability, and icing intensity, where high structures are concerned, when ground values are used, because the processes involved in the formation of deposits in the air layer near the ground, and at heights up to 1000 m, often occur independent of each other. It therefore would appear that at the present time the only applicable method for calculating the probability of icing of high structures is an indirect one, one that considers the occurrence of meteorological conditions that favor ice formation.

Reference [2] gives the frequency of conditions that favor the icing of high structures.

This paper deals with the principles of the indirect method for calculating the intensity of ice deposits, a method that was developed at the Main Geophysical Observatory by V. G. Gluchov under the guidance of M. V. Zavarina [4]. The experimental calculations for this paper were made by M. N. Mytarev.

It is known that the formation of glaze ice and rime deposits is the result of supercooled fog, or droplets from clouds, settling on structures and then freezing, of wet snow adhering to structures, and of the sublimation of water vapor.

The reference size of circular and cylindrical elements (wires, ropes, cables, rods, etc.) was fixed at a diameter of 10 mm (11, 12] for the calculation of ice loads, so the method presented below, and the parameters, are with reference to these elements. The ice load, that is, the weight of the glaze ice and rime that deposits on one meter of wire or rod with moisture transport normal to the wire/rod, can be determined, approximately, by using the equation

$$P_s = \rho_w \int_0^{\tau} \tilde{E}\beta w v d\, d\tau \tag{1}$$

where $\tilde{E}$ is the completely integral deposit coefficient that indicates the extent of the settling of the water droplets as a result of inertial forces (the droplets having a given size distribution) on the surface of the member. $\tilde{E}$ is numerically equal to the ratio of the number of droplets that settle on the surface of the member in unit time to the total number of droplets that are contained in the air volume transported through its axial cross section; β is the freezing coefficient, numerically equal to the ratio of the number of freezing droplets to the total number of settling droplets; w is the water content in the clouds (kg/m^3); d the small diameter of the deposit of a fixed member, with consideration given to diameter (d_0); τ is the time (in sec); v is the wind speed (in m/sec), and ρ_w the density of the water, which is equal to 10^3 kg/m^3.

In accordance with [8], $\tilde{E}$ can be found from

$$\tilde{E} = \frac{3^6}{5!\, r_m^6} \int_0^{\infty} r^5 e^{-\frac{3r}{r_m}} E(r)\, dr \tag{2}$$

where

r is the droplet radius, μ;

r_m is the mean droplet radius, μ; and

E(r) is a function characterizing the dependence of the completely integral deposit coefficient on droplet size r, and wind speed v.

Figure 1 shows $\tilde{E}$ as a function of wind speed, v, and wire diameter, d_0, when $r_m = 4.5\ \mu$. Similar curves were plotted by V. G. Gluchov for $r_m = 5, 6$, and $7\ \mu$. These are the limits within which the mean droplet radius fluctuates in stratus, stratocumulus, and nimbostratus clouds [8, 13].

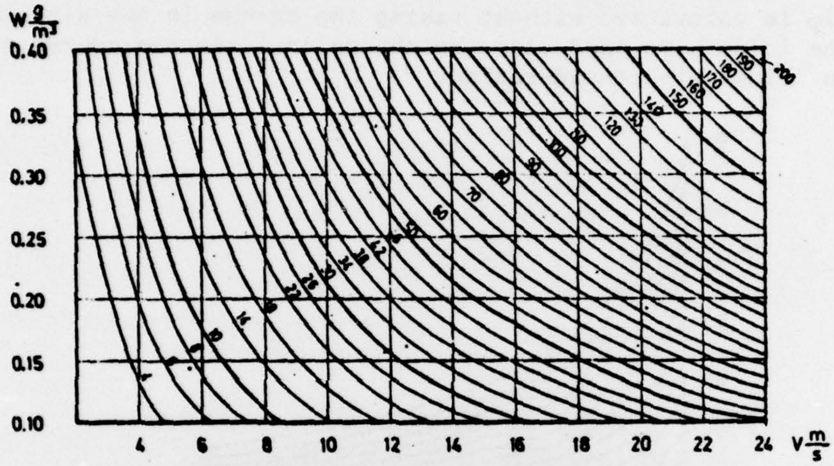

Figure 1. The completely integral deposit coefficient $\tilde{E}$ as a function of wire diameter (mm), at different wind speeds.

Freezing coefficient β *is determined from* the heat balance equations for the frozen surface. It depends on a great many of the meteorological parameters listed above, on air temperature, t, and on the size distribution of the droplets

$$\beta = f[v, d, t, w, r_m, n(r)] \qquad (3)$$

where n(r) is the droplet size distribution function. However, $\beta \approx 1$ [4] for those values of v, t, w and r_m which are characteristic of conditions under which icing of high structures occurs, and for structural members with $d \geqq 10$ mm.

The temporal change in v, w, $\tilde{E}$, and d contained in the equation [1] is unknown, so their mean values are determined for the approximate calculation of ice loads, and

$$\begin{aligned} d &= d_0 = \text{const} \\ P &= \varrho_w \tilde{E}_m \bar{v} \bar{w} d_0 \tau \end{aligned} \qquad (d_0 \text{ is wire diameter without ice deposit}) \quad (4)$$

is assumed. $\tilde{E}_m$ is found as a function of $\bar{v}$ and d_0 using the curves in Figure 1.

Assuming that $\tau = 1$ hour, and $d_0 = 10$ mm, Eq. (4) will yield the term for finding the intensity of growth of the deposit, I_p [kg/m·h], for 10 mm of wire,

$$I_p = 36\,\bar{E}_m \bar{v}\bar{w}\,. \tag{5}$$

Figure 2 is the nomogram derived from Eq. (5). $r_m = 5\ \mu$ was used in the calculations for deriving the nomogram. E_m is found as a function of $\bar{v}$ from a nomogram analogous to that shown in Figure 1. When $d = d_O$ = constant, I_P is calculated without taking the change in the size and shape of the icing wire (and also the change in $\tilde{E}$) in the course of the increase in icing into consideration.

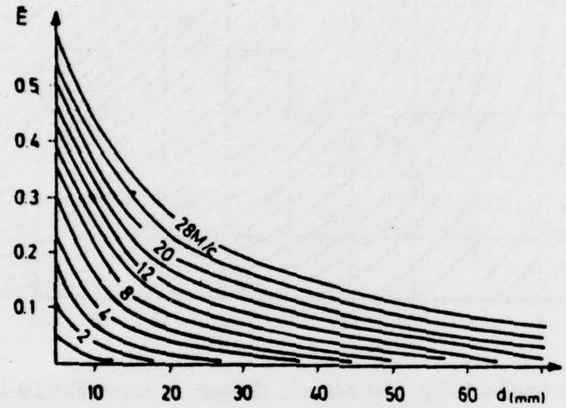

Figure 2. Rate of growth of glaze ice and rime deposits (g/m·h) as a function of water content in clouds, $\bar{W}$ (g/m^3), and wind speed, vI [sic] (m/sec). $\bar{\tau} = 4.5 \cdot 10^{-4}$ m/sec.

These changes can be taken into consideration when k is introduced into the working equation, Eq. (4), the coefficient being determined by the relationship

$$k = \frac{P_s}{P} = \frac{\varrho_w \int_0^\tau \bar{E}\beta w v d\, d\tau}{\varrho_w \bar{E}_m \bar{u}\bar{w} d_0 \tau} \approx \frac{\varrho_w \sum_{i=1}^{\tau} E_i v_i w_i d_i \Delta\tau}{\varrho_w \bar{E}_m \bar{v}\bar{w} d_0 \tau} \tag{6}$$

Replacing v_i and w_i with the mean values for the growth rate (which introduces no significant errors into the calculation), we obtain

$$k = \frac{P_s}{P} \approx \frac{\sum_{i=1}^{i} \bar{E}_i a_i \Delta\tau}{\bar{E}_r d_0 \tau} = f(v, d)\,. \tag{7}$$

The magnitude of k depends on the shape of the cross section of the iced member, its small diameter, and wind speed during growth. Experimental observations at the masts in Obninsk and Ostankino [6] showed that the shape of the cross sections of the members changed little at first under persistent (longer than 24 hours) icing of fixed circular and cylindrical members with a cross section of 10 mm, but then became elliptical (and continued to increase in ellipticity until the shape was almost rectangular by the end state, with the small deposit diameter remaining constant during this stage).

Total growth time therefore can be divided conditionally into three stages of equal duration, and a specific cross sectional shape can be assumed for each stage (a circle with increasing diameter for the first stage, an ellipse with increasing ratio between the major and minor axes for the second stage, and a rectangle with constant width for the last stage), when calculating the changes in $\bar{E}$ and d.

The magnitude of k was found for values of w_i within limits 0.05 to 0.30 g/m^3, v_i within limits 1 to 25 m/sec, and α_1 within limits 15 to 100 mm.

Calculations showed that k values do not depend on the nature of change in v_i during the growth process for given d_i, but only on $\bar{v}$. It was found that k changes within limits 1.06 to 1.74 when $2 \leq \bar{v} \leq 24$ m/sec and $15 \leq d \leq 100$ mm.

The load closest to the real load can be approximated by introducing k into Eq. (4). This load cannot be calculated directly because observations of v, w, and d are not frequent enough.

Thus,

$$P_x \approx kP \approx kE_m \bar{v} \bar{w} d_0 \tau . \tag{8}$$

When τ = 1 hour and d_0 = 10 mm

$$P_x \approx kI_p \tau . \tag{9}$$

The ice load probabilities, P_x, are found by using maximum annual distributions [15]. It is best to use two P_x maxima for each year when the observation period is short. These values will be found during the period of maximum duration of the existence of supercooled clouds at each level. The distribution of P_x values is found by using the Fisher-Tippet function type II [2],

$$\varphi (P_x \leq x) = \varphi (P_x) = e^{-\left(\frac{x}{\beta}\right)^{-\mu}} \tag{10}$$

where

φ is the probability that the ice load, P_x, is smaller than x;

μ *and* β *are distribution parameters that depend on area physico-geographic and climatic conditions.*

The integral curve of P_x values is sufficiently well reflected in a coordinate grid with coordinates log P_x and log[-log $\varphi(P_x)$], and the P_x values can readily be taken from the coordinate grid with the accuracy required.

It is known that prolonged presence of a thick, deep cloud cover over any point usually is associated with frontal passages. The thickness of frontal stratus-stratocumulus clouds, according to data in [1, 5, 13], is at least 500 to 600 m, that of nimbostratus clouds up to 2 km. When determining τ at greater altitudes, it is assumed that the cloud layer extends to a height of 600 m, with the lower cloud limit 100 m.

Ice loads were calculated as follows.

1. The longest periods of continuously present deep clouds at subzero temperatures, those that correspond to long periods of growth of deposits, were taken from meteorological observation tables.

2. Air temperature and mean wind speeds at heights of 100, 200, 300, 500, and 600 m were determined for each of the periods by using aerological observation tables.

3. The intensity of growth of deposits, $\underline{I}_p$, was taken from the nomogram (Figure 2) using the values of $\bar{v}$ and $\bar{w}$, with the mean water content of the clouds taken from reference [5].

4. The deposit weight, $P_x = kI_p$, was calculated for each of the periods with increasing ice deposits, using Eq. (9).

Maximum ice loads were determined with evaporation and melting processes of the deposits taken into consideration.

Evaporation of the deposits occurred at subzero temperatures when the cloud cover rose above the given altitude, or when few clouds, or clear weather, were observed.

The amount (weight) of the evaporated ice was found by using the mean evaporation intensity [10 (g/m·h)], which was calculated by using the observation data obtained from the mast in Obninsk.

The deposit cycle ended when the deposit evaporated completely over a period between times of increasing deposits, or the remaining deposit became a part of the following deposit cycle, etc., until the deposit completely disappeared.

Melting, with subsequent destruction of the deposits, was observed when the air temperature rose above 0°C. These processes were very intensive and deposits, regardless of weight, were destroyed by melting in a few hours, so the time at which above-zero temperature occurred was taken as the end of the deposit cycle.

Another, important, factor in ice formation, that of supercooled liquid precipitation, was taken into consideration in indirect calculations of ice loads, and this was in addition to the cloud cover during subzero air temperatures.

Two types of precipitation are to be distinguished, depending on intensity and size of droplets; drizzle and heavy rain.

Generally speaking, the settling behavior patterns, the result of inertia, characteristic of icing processes in clouds, continue to be present in the icing of objects in an area in which supercooled liquid precipitation occurs. The deposit coefficient, $\tilde{E}$, becomes greater than that for cloud droplets because of the larger diameter of the falling particles.

The intensity of glaze ice formation on a cable in rain or drizzle was calculated using an equation similar to that at Eq. (4)

$$P' = \tilde{E}'\beta'\tau'\varrho_w d_0 v_r \qquad (11)$$

where

$\tilde{E}'$ and β' are droplet deposit and freezing coefficients, respectively;

$\bar{w}'$ is the mean water content of the precipitation;

τ' is the period of precipitation;

d_0 is the diameter of the structural members; and

v_r is the speed of droplet motion.

$v_r = \sqrt{\bar{v}^2 + vg^2}$, where v_g is the speed of fall of the droplets found [16]. The mean size of precipitation particles was taken to be 150 μ, and that of rain drops to be 500 μ, according to data found in references [9, 14].

Calculations found $\tilde{E} \approx 1$ for rain and drizzle droplets when d_0 = 10 mm.

Rain intensity was taken to be 3 mm/h for approximate calculations, and corresponded to a water content of 0.16 g/m^3. Drizzle intensity was taken to be 0.2 mm/h (water content 0.07 g/m^3).

The freezing coefficient for the values listed for d_0 and $\tilde{E}'$ was almost 1 for temperatures below -2.5°C.

Calculations found that intensity Ip' (deposit growth rate), attributable to liquid precipitation (and taking into consideration the fact that here wind speeds generally do not exceed 7 to 8 m/sec), was 1 to 16 (g/m•h) for drizzle, and 2 to 32 (g/m•h) for rain.

By way of comparison, the calculated intensity, I_p, in the growth of deposits was 4 to 80 (g/m•h), and fluctuated between 0.5 and 103 (g/m•h), according to experimental values for deep supercooled clouds, when $\bar{v}$ = 2 to 16 m/sec, and water content in the clouds was 0.05 to 0.25 g/m^3.

Thus, the intensity of glaze ice formation in an area of liquid precipitation is comparable to the intensity of the growth in deposits in deep clouds, although more intensive ice formations often can be observed in these clouds, particularly when speeds are 12 to 16 m/sec.

Results of indirect calculations of ice loads at heights of 100 to 600 m at the Aktyubinsk station (observation period 1960 to 1969) follow. Loads were found for ice formation in clouds and for precipitation, with evaporation, and melting of the deposits, taken into consideration.

Figure 3 is the integral curve for the distribution of the annual ice load maxima at 300 m. Table 1 lists the ice load probabilities, taken from the figure.

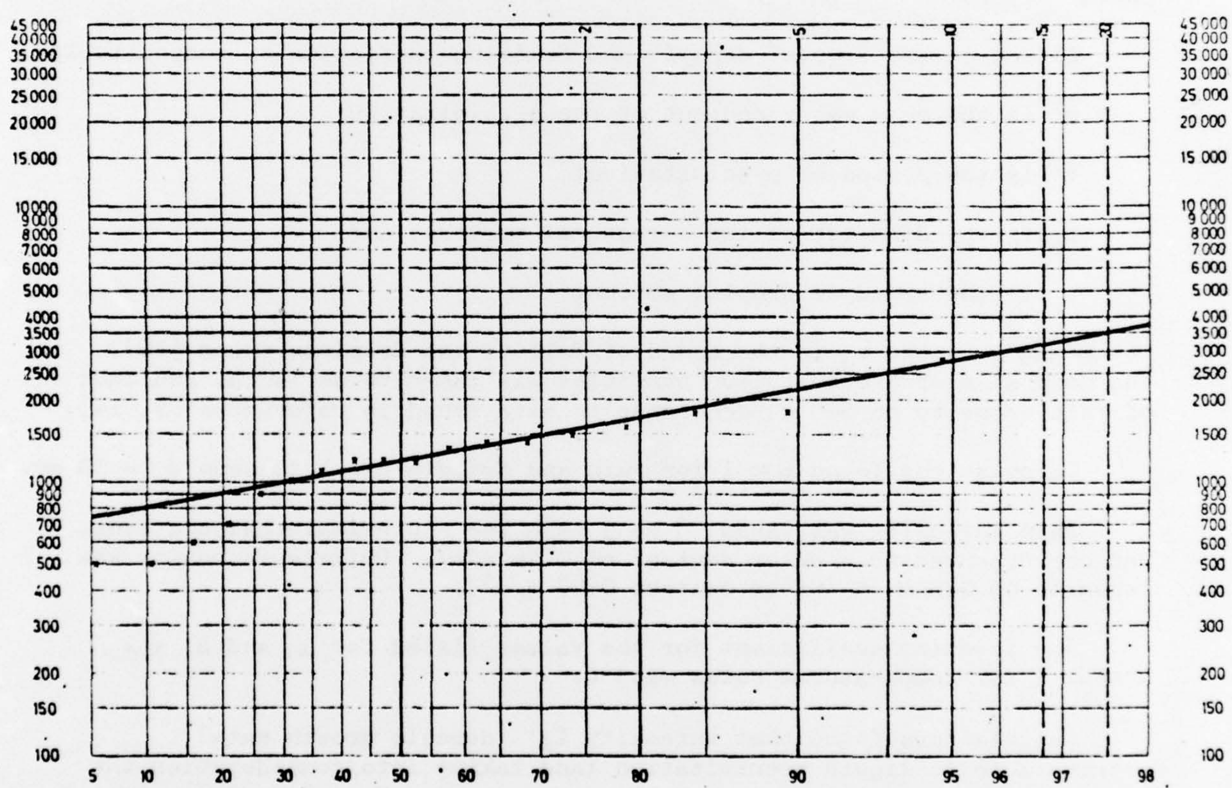

Figure 3. Integral curve for ice load distribution at 300 m in Aktyubinsk.

In this table, P_2, P_5, P_{10}, P_{15}, and P_{20} are the maximum deposit weights that can occur once in 2, 5, 10, 15, and 30 years.

Table 1 shows that P increases with various degrees of reliability from 100 to 500 m, with a large increase in P occurring in the 300 to 500 m layer.

Table 1

Ice Load Probabilities, P, in the 100 to 600 m Layer

Height [m]	P_2 [kg/m]	P_5 [kg/m]	P_{10} [kg/m]	P_{15} [kg/m]	P_{20} [kg/m]
100	0,5	0,8	1,1	1,4	1,6
200	0,8	1,2	1,5	1,7	1,9
300	1,6	2,2	2,8	3,2	3,5
500	2,8	3,9	5,0	5,9	6,5
600	3,2	4,2	5,3	6,0	6,5

The indirect method of calculating ice loads was found to be accurate by comparing it with glaze ice and rime deposits measured between 1963 and 1969 on rods with d = 15 mm on the Obninsk mast at heights of 200 and 300 m. Similarly, the values of the standard ice cover thickness, b, were compared. These were obtained by using the measured, and calculated, magnitudes of the loads, P.

The standard ice cover thickness, b, is the thickness of a cylindrical ice cover with a density of 0.9 g/cm^3, that uniformly covers a cable with a diameter of 10 mm suspended at a height of 10 m [15]. The magnitude of b was calculated by using

$$b = \sqrt{\frac{P}{283} + \frac{d^2}{4}} - \frac{d}{2} \tag{12}$$

The P and b probability values were found by resort to the statistical extrapolation method discussed above. The integral curves were plotted from the distribution of the two maximum annual P and b values, and these were obtained from observations and by the indirect method.

The relative error in the indirect method for calculating maximum annual ice loads was established, and was found to vary between 0 and ±36% at heights of 200 and 300 m. The error in P is somewhat less at these heights, between 0 and ±30%.

Table 2 lists the results of a comparison of P and b probability values. The table shows the experimental and calculated values with the subscripts 1 and 2, respectively; $r_P = (P_2 - P_1/P_1) \cdot 100$ is the relative error in the determination of the calculated ice load, $r_b = (b_2 - b_1/b_1) \cdot 100$ is the relative error in the ice cover thickness calculated using the indirect method, T is the repetition period during which the calculated magnitude can be exceeded once.

The table shows that errors in the indirect method of calculating the P and b probabilities are smaller than those for individual (maximum)

P and b values for each year. They vary from -2 to -19% for the ice load, and from 0 to -11% for the ice cover thickness given, with the scope of the error increasing with increase in the repetition period, T.

Table 2

Calculated and Experimental Values of Ice Load and Ice Cover Thickness Probabilities

Height [m]	T [Years]	P_1 m[g/m]*	P_2 [kg/m]	b_1 [mm]	b_2 [mm]	r_P [%]	r_b [%]
	2	1,25	1,22	16	16	− 2	0
200	5	1,80	1,64	21	19	− 9	−10
	10	2,33	2,04	24	22	−12	− 8
	2	3,50	3,04	31	28	−13	−10
300	5	4,60	3,90	36	32	−15	−11
	10	5,70	4,60	40	36	−19	−10

*Translator's Note. Should be [kg/m], same as for P_2.

The method for calculating ice loads on high structures under discussion using indirect data obviously is sufficiently accurate for finding the maximum ice weight and standard ice cover thickness values, as well as their probabilities.

What remains to be developed is a method for calculating icing intensity during wet snow.

Values obtained from meteorological and aerological observations of supercooled clouds and precipitation can be used to arrive at an indirect determination of certain other characteristics of the ice regime in the boundary layer (duration of icing, temperature, and wind under ice conditions).

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[See end for English translation of titles.]

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